7. Implications of the Mineralogic Record for Fast-Path Recognition

The preceding work suggests that fast pathways are distinctive in terms of structural settings, their associated hydrologic properties, and surficial factors affecting infiltration. We are also investigating whether the attributes of fast pathways contribute to the formation of distinctive secondary mineral assemblages as well. Mineralogic studies of samples collected for isotopic analysis will help establish the geochemical context of fast fluid pathways. Equally important is the insight about small-scale in situ differences in infiltration pathways and fracture-matrix interaction to be gained from studies of mineral distributions around fast flow paths.

Studies of void-filling minerals in surficial pedogenic deposits and in the subsurface (e.g., Vaniman et al., 1995; Paces et al., 1996) suggest that the most common secondary minerals deposited during the last few hundred thousand years are calcite, opal, and clays. Manganese minerals are abundant, as well. Syngenetic minerals such as the high-temperature silicates, have not been deposited in the Quaternary, but documentation of their distribution is an aid in reconstructing the origins of fast pathways.

In addition to minerals deposited from solution, secondary deposits in the ESF rock also include accumulations of transported particulate material. Deposits of clays and coarser-grained materials can be some of the best indicators of saturated versus unsaturated conditions in the fractures and other void spaces at the time of deposition.

Thus far, the detailed mineralogy and petrology have been described for 39 of the ^{36}Cl samples, as summarized in this section and in Table II, based on detailed descriptions in Appendix C. These 39 samples include 8 systematic samples plus 31 feature-based ones. Nineteen of the samples are from known fast paths insofar as they contain unambiguous levels of bomb-pulse ^{36}Cl.

TABLE II
Structural Settings, ^{36}Cl/Cl Values, Presence of Bomb-Pulse ^{36}Cl, and Secondary Mineralogy of ESF Sample Sites

Sample[1]	Station	Sampled feature[2]	Corrected ^{36}Cl/Cl $\times 10^{-15}$	Presence of bomb-pulse ^{36}Cl[3]	Calcite	Opal[4]	Clay/Mord.[5]	Clay/Mord. 2 or more[6]	Feldspar±Cr. Silica±Fe-Ti oxides[7]	Transported Particulates[8]	Mn minerals	Other mineral(s)[9]
E001	1+98	fault breccia	518[10]	-	-	-	●	-	●	●	●	-
E008	1+99.8	fault breccia	2132	●	●	-	●	-	●	●	●	-
E010	1+99.8	fault breccia	722	-	-	-	●	-	?	●	●	-
E011	1+99.8	fault breccia	2424	●	●	●	?	?	?	●	●	-
E007	2+3	bedrock	519	-	-	-	-	-	-	-	-	-
E073	5+04	fracture	468	-	-	-	●	-	-	-	●	-
E028	12+44	cooling jts.	2632	●	-	-	-	-	●	●	-	●
E029	13+00	bedrock	640	-	-	-	-	-	●	-	-	-
E030	13+67	cooling jts.	1613	●	-	-	-	-	●	-	-	-
E031	14+00	shear zone	2399	●	-	-	-	-	●	-	-	-
E033	14+41	fault breccia	876	-	●	●	-	-	●	-	-	-
E035	15+05	fracture	628	-	●	●	●	-	●	-	●	-
E036	16+12	cooling jt.	382	-	●	●	-	-	●	-	-	●
E037	16+19	fracture	982	-	-	-	●	-	-	●	-	-
E038	17+00	bedrock	716	-	-	-	-	-	●	-	●	-
E040	18+96	broken rock	1642	●	●	-	●	-	●	-	-	-
E041	19+00	bedrock	746	-	-	-	-	-	●	-	●	-
E042	19+31	breccia	3023	●	●	-	-	-	-	-	-	-
E044	19+42	breccia	2290	●	●	-	-	-	●	-	-	-
E045	21+00	bedrock	799	-	-	-	-	-	●	-	-	-
E046	22+71	fractures	863	-	●	-	-	-	●	-	-	-
E047	23+00	bedrock	663	-	-	-	-	-	-	-	-	-
E050	24+40	fault breccia	2579	●	●	-	-	-	●	-	-	-
E020	24+68	fracture	814	-	●	●	-	-	●	-	-	-
E052	26+79	shear zone	2036	●	●	-	-	-	●	-	-	-
E141	29+00	bedrock	922	-	-	-	-	-	●	-	-	-
E142	29+21	fracture	583	-	●	-	-	-	-	-	-	-
E144	29+73	cooling jt.	815	-	●	-	-	-	-	-	-	-
E149	31+64	cooling jt.	631	-	●	-	●	-	-	-	●	-
E150	33+00	fr. bedrock	1337	●	-	-	-	-	-	-	●	-
E152	34+28	fr. bedrock	4105	●	●	-	-	-	-	-	-	-
E153	34+32	cooling jts.	3291	●	●	-	-	-	-	●	●	-

TABLE II (cont.)
Structural Settings, ^{36}Cl/Cl Values, Presence of Bomb-Pulse ^{36}Cl, and Secondary Mineralogy of ESF Sample Sites

Sample[1]	Station	Sampled feature[2]	Corrected ^{36}Cl/Cl $\times 10^{-15}$	Presence of bomb-pulse ^{36}Cl[3]	Calcite	Opal[4]	Clay/Mord.[5]	Clay/Mord. 2 or more[6]	Feldspar±Cr. Silica±Fe-Ti oxides[7]	Transported particulates[8]	Mn minerals	Other mineral(s)[9]
E154	34+71	cooling jts.	3794	(●)	●	-	-	●	-	●	●	-
E155	35+00	bedrock	1013	-	-	-	●	-	●	●	●	-
E157	35+03	cooling jts.	1335	(●)	●	-	-	-	-	-	●	-
E158	35+08	cooling jts.	2586	(●)	●	-	-	●	-	-	●	-
E160	35+45	cooling jts.	3529	●	(●)[11]	-	-	●	●	●	●	-
E161	35+58	cooling jt.	2146	(●)	●	-	-	●	●	-	●	-
E175	35+93	fault breccia	2840	(●)	(●)[11]	-	-	●	●	●	●	-

[1]Samples were divided into separate splits for isotopic and mineralogic analysis. Mineralogic data were also recorded for the sample sites In cases where more than one split of a sample was measured for chlorine isotopic ratios, the value reported in this table is the highest value obtained.
[2]Abbreviations: cooling jt. = cooling joint; fr. bedrock = fractured bedrock.
[3]The black dot symbol in this column denotes samples containing a component of bomb-pulse chlorine (^{36}Cl/Cl values > 1250×10^{-15}) inferred to be less than 40 years old. Parentheses around the symbol indicate that bomb-pulse values were measured in a sample or sub-sample closely associated with the mineralogically characterized sample. A dash indicates an absence of evidence for a component of bomb-pulse water.
[4]As used here, opal is transparent, colorless to light-colored, and typically fluoresces yellow-green in short-wave UV light. X-ray diffraction analysis of selected samples indicates opal-A.
[5]This category includes clay and/or mordenite.
[6]An entry in this column indicates the presence of two or more distinct deposits of different colors, as identified by binocular microscopy.
[7]This category includes minerals inferred to be of early to late syngenetic origin. Reported occurrences in this category are limited to minerals in growth position on the rock surfaces. Cr. Silica = crystalline silica, including quartz, chalcedony, cristobalite, tridymite, opal-CT.
[8]This category includes physically transported particulates, mostly silt- and sand-size material. Deposits of clay-size material are not included here.
[9]This category includes fluorite and unidentified minerals.
[10]Data from Appendix B.
[11]Calcite was not present in the aliquot for mineralogic characterization but was observed in fractures at the collection site (E160) or in fractures adjacent to the fault (E175).

7.1. History of Secondary Mineral Deposition

Deposition of secondary minerals in and adjacent to fractures and other void spaces began very soon after the ash flows were deposited and has continued in the Quaternary. The general chronology of secondary-mineral deposition has been established by many studies and continues to be refined (e.g., Levy and O'Neil, 1989; Cowan et al., 1993; Levy et al., 1996; Whelan et al., 1996; Paces et al., 1996). The brief summary given here emphasizes aspects of mineral deposition that are helpful for documenting the origins and longevity of transmissive features.

Vapor-phase crystallization in fractures and lithophysal cavities (gas pockets) is a high-temperature process that occurs early in the cooling history of an ash flow deposit. The vapor-phase mineral products are most prominent in the upper portions of the Tiva Canyon and Topopah Spring Tuffs. Late-stage syngenetic minerals that formed at ambient or near-ambient temperature include quartz, chalcedony, opal-CT, and opal-C. Some calcite and opal-A also formed under these conditions (Whelan et al., 1996; Levy, 1993). Many other minerals likely crystallized during the late stages of cooling; among these are smectite, mordenite, heulandite-clinoptilolite, potassium feldspar, apatite, and zircon (Levy et al., 1996).

For the past 11 million years or so since the decline of major volcanic activity near Yucca Mountain, the rocks of the ESF have remained in the unsaturated zone (Levy, 1991). The rocks did not experience the pervasive diagenetic or hydrothermal alteration that affected rocks at greater depth. During at least the last few hundred thousand years, secondary-mineral deposition of calcite, opal, and clay represents the main mineralogic modification in the shallow unsaturated zone (e.g., Vaniman et al., 1995; Paces et al., 1996). Many geochemical attributes of the calcites reflect soil-zone processes and interactions with infiltrating water (Whelan and Stuckless, 1992). The extent to which clays in the unsaturated zone, particularly in the PTn, are the products of late-syngenetic alteration versus localized diagenetic alteration related to perched water is under investigation (Levy and Chipera, 1997).

7.2. Calcite

Examination of the subset of analyzed samples for which mineralogic data are available shows that calcite is usually present at sample sites that have received infiltration during the last 40 years (Table II), with 15 of 19 bomb-pulse values obtained for samples containing calcite. By comparison, calcite is present in only 8 of the 20 samples in which no discernible bomb-pulse signal is present, or 8 out of 12 if systematic bedrock samples are excluded. Between Sta. 17 and 36, calcite is present at every feature-based sample site, but 14 of the 19 feature-based sites in this interval are also bomb-pulse sites. Thus, in intervals where calcite is not common, bomb-pulse sites are somewhat more likely to contain calcite; the interval where calcite is common also contains a relatively large number of bomb-pulse sites. These associations certainly do not by themselves provide a highly reliable basis to predict the locations of fast paths. The data base of mineralogic data is not yet large enough for statistical analysis, but a few interesting observations arise from a comparison with the line-survey data on calcite distribution in the ESF (Paces et al., 1996). The line survey has identified an interval between Stations 12 and 17 in which calcite is relatively common and an interval between Stations 17 and 22 in which it is rare. Three ^{36}Cl samples collected between Stations 14 and 17 do contain calcite, but four samples collected between Stations 12 and 14, including three bomb-pulse samples, contain no calcite. The six samples from Stations 17 through 22 include three bomb-pulse samples, all of which contain calcite. These comparisons are far from conclusive, but they suggest the possibility that in some intervals the mineralogy of fast paths shows trends contrary to general patterns of mineral distribution.

We have observed in a qualitative sense that calcite deposits in many of the bomb-pulse samples have thicknesses less than about a millimeter. In some cases, this reflects the size of the aperture in which the calcite grew. At least some examples exist of thin calcite coatings in samples with sufficient pore spaces for thicker coatings to have grown; sample E008, a Bow Ridge fault breccia, is one example. These calcite deposits are much thinner than the several-cm-thick aggregates from which multiple layers have been dated by $^{230}Th/U$ methods (Paces et al., 1996). The thin calcite coatings may record shorter segments of depositional history or the depositional layers may be thinner due to slower deposition rates than those calculated for other ESF sites (Paces et al., 1996). Either explanation would have significant, though different, implications for differences between bomb-pulse transmissive features and other calcite deposition sites. For example, if fast-path calcites record a shorter and mostly more recent depositional history, geochronologic data from these samples could help elucidate the initiation and longevity of the fast-path function.

7.3. Opal

Amorphous opal (opal-A) is much less common than calcite in the samples and is associated with only one of the bomb-pulse samples from the Bow Ridge fault zone (E011). Furthermore, only five of the 32 fractured samples (16%) contain opal. This finding was unexpected because the line-survey data of Paces et al. (1996) suggest that opal, although less abundant and less widely distributed than calcite, is still a very common secondary mineral in the ESF, at least as far as Sta. 30. Because opal, where present, generally occurs only with calcite (Whelan et al., 1996), the apparently low abundance of opal in our sample set could be partly linked to processes responsible for the lesser thicknesses of calcite deposits in fast pathways.

7.4. Clays

Clays, predominantly smectites, are nearly ubiquitous in the major rock units of the ESF. Smectite contents of about 1 to 10 wt % are common in bulk samples of the devitrified Tiva Canyon and Topopah Spring Tuffs (Bish and Chipera, 1989; Chipera et al., 1995; Chipera et al., 1996). The clay represented by the bulk analyses of these rocks is disseminated throughout the matrix. As the result of *in situ* alteration, the matrix clay content of the PTn can be as high as ~95 wt % (Levy et al., 1996).

The clays reported in Table II are all fracture or breccia clast coatings rather than matrix components. The presence of these deposits is assumed to result from aqueous transport of fine clay particles within the fracture network because clays would not be readily released from the local densely welded rock matrix. The actual sources of the clays and the distances of transport have not been determined. Multiple clay deposits are distinguishable by color and, in some cases, by differences in distribution on the rock surfaces. These distinctive deposits were derived from different source materials and may have been transported and deposited at different times.

The potential implications of clay deposits coating fractures or breccia clasts are twofold. First, the constituents of these clay deposits were transported as particulates rather than as solutes and are unlikely to have been derived directly from the adjacent rock matrix. Such transport requires a significant component of fluid flow in the fractures that was distinct from any influx that might be received from the matrix. Second, the heterogeneity of clay deposits in a sample indicates that the sample site has received aqueous input from rocks that experienced different alteration processes. We hypothesize that input from multiple sources is more likely to occur along fluid pathways offering the greatest continuity of fracture transport, possibly across lithologic units, and therefore the greatest accessibility to different clay sources. The existence of a component of fluid traveling almost exclusively through fractures, with a high interunit continuity of flow path, is a predicted attribute of fast pathways.

For the samples included in Table II, clay/mordenite is present in 15 out of 39 samples or 39%. Eight of the 19 bomb-pulse samples, or 42%, contain clay/mordenite. The mineralogic data set, taken as a whole, does not indicate an association between fast paths (as indicated by the presence of bomb-pulse ^{36}Cl) and the presence of clay/mordenite. However, in the interval from Sta. 34+71 to Sta. 35+93 (Sundance fault) there is a high incidence of both bomb-pulse $^{36}Cl/Cl$ values and clay/mordenite. Six out of seven samples (86%) have the bomb-pulse signature, six out of seven samples contain clay/mordenite, and five of the six bomb-pulse samples (83%) contain clay/mordenite.

7.5. Transported Particulates

For particulates larger than clay particles, it is possible in many cases to determine whether they are different from the local bedrock and have therefore been transported to their present location from elsewhere in the geologic section. It is relatively easy to recognize samples in which the fine particulates are highly enriched in vapor-phase or hydrothermal minerals relative to their abundance in the local bedrock, and this is a good preliminary criterion for documenting evidence of particulate transport. Vapor-phase particulates are typically mixtures of very well formed <1-mm crystals of tridymite, cristobalite, alkali feldspar, quartz, biotite, Fe-Ti oxides, and hematite. Compared to a devitrified bedrock, vapor-phase materials may also contain a higher proportion of silica minerals (tridymite, cristobalite, and quartz) relative to alkali feldspar. Table III shows the mineralogy of two textural constituents of the Bow Ridge fault breccia in ESF sample E008. The data suggest that the powdery white material that acts as a weak cement has a higher ratio of silica minerals to feldspar than do the calcite-cemented bedrock breccia clasts. However, a high uncertainty associated with the feldspar content of the white material renders the comparison statistically insignificant. The errors of measurement could be reduced by the use of longer counting times for the X-ray diffraction analysis. At this site within the lower lithophysal zone of the Tiva Canyon Tuff, local sources exist for the vapor-phase particulates and therefore they need not have been transported very far. However, a substantial amount of vapor-phase particulates had to be transported, probably from overlying rocks rich in vapor-phase material, to form the ubiquitous white coatings on the bedrock breccia clasts in the fault zone. The presence of translocated particulates within a flow path attests to the existence of connected pore spaces with apertures large enough to permit the passage of the particulates.

TABLE III
Quantitative X-Ray Diffraction Results for Bow Ridge Fault Breccia, ESF North Ramp
(weight percent)

Sample	Smectite	Tridymite	Cristo-balite	Quartz	Feldspar	Calcite	Hematite	Total
E008, bedrock breccia clasts	4±2[1]	3±1	6±1	4±1	23±4	60±6	n.d.[2]	100±7
E008, <150 μm fraction, powdery white cement	16±6	10±2	9±4	11±2	46±10	7±2	1±1	100±13

[1]2-σ standard deviation.
[2]"n.d." signifies the phase was not detected.

Sample E037-2, from Sta. 16+19 in the Topopah Spring Tuff, offers a dramatic example of particulate transport. The wall rock is densely welded, devitrified tuff, but the fracture filling consists of devitrified rock fragments in a fine-grained matrix of glass pyroclasts. Several sequences of graded bedding are preserved within the fillings. Graded bedding is produced by settling of particles in a water-filled fracture. The glassy constituents came from tens of meters higher in the stratigraphic section.

Despite the evidence of fluid flow sufficient to transport silt-size particulates tens of meters in the fracture, this sample does not have a bomb-pulse $^{36}Cl/Cl$ signature. A number of factors unrelated to the hydrologic properties of this specific fracture may be responsible. The most likely explanation is that the particulate fillings were deposited before the PTn nonwelded tuffs were emplaced on top of the Topopah Spring Tuff. In numerical simulations of infiltration, the PTn dampens out the effects of episodic high-infiltration events (Fabryka-Martin et al., in press) so that particulate-laden flow sufficient to saturate a fracture in an underlying unit would be unlikely to occur. Remobilization of nonwelded pyroclasts would also have been more feasible before the tuffs were compacted by the addition of new overburden. This one-time fast path may have been isolated from the surface by later pyroclastic deposition, and a throughgoing connection may never have been re-established.

The significance of transported particulates is similar to that of clay deposits, described above, but possibly less valuable as a fast-path recognition criterion. As in the E037-2 example, particulate deposits may relate more to former than to present fast pathways as far as the Topopah Spring Tuff is concerned.

7.6. Feldspar, Crystalline Silicas, and Fe-Ti oxides

This category of syngenetic minerals includes alkali feldspar, tridymite, cristobalite, quartz, opal-CT (opal with short-range cristobalite and tridymite ordering), opal-C (opal with short-range cristobalite ordering), chalcedony (fibrous microcrystalline quartz), hematite, and other Fe-Ti oxides. Each of the tuff units exposed in the ESF contains some or all of these phases that formed as it cooled. In particular, feldspar, tridymite, cristobalite, and the Fe-Ti-oxides are known as vapor-phase minerals deposited at high temperatures very early in the cooling history of a tuff (e.g., Carlos, 1985). The main significance of syngenetic minerals is that their presence in growth position on fracture walls, breccia fragments, or other secondary pore surfaces establishes the early origins of these transmissive features. For example, the vapor-phase-altered breccias at Sta. 35+93 (sample E175) document the early intraformational origin of this zone of deformation which is now part of the Sundance fault.

7.7. Manganese Minerals

No definitive mineral identifications have been made for the generally ≤1-mm deposits of Mn minerals present in many of the samples collected for this study. X-ray diffraction and scanning-electron microscopic studies of drill core of the Tiva Canyon and Topopah Spring Tuffs in the unsaturated zone have identified rancieite (Ca-bearing hydrous Mn oxide) and lithiophorite (Li-, Al-bearing hydrous Mn oxide) as the dominant Mn phases (Carlos et al., 1993). Notations of the presence of Mn minerals, as used in Appendix C and Table II, refer only to Mn minerals on the surfaces of rock materials. Manganese minerals within the rock matrix cannot be detected by stereomicroscopy.

For samples from the Topopah Spring Tuff (Sta. 12+44 through 35+93, Table II), a transition from uncommon to nearly ubiquitous Mn minerals corresponds very approximately to the boundary between the upper lithophysal and middle nonlithophysal zones. This boundary marks a downsection change from less frequent and shorter fractures to more frequent and longer ones. This observation is consistent with core-based observations of Carlos et al. (1993) that Mn coatings are especially abundant on smooth-surfaced cooling joints, which are most common in the middle nonlithophysal zone.

The link between Mn mineral occurrence and fracture characteristics associated with syngenetic zonation implies than these minerals are unlikely to be good predictors of fast pathways in the unsaturated zone. There is a possibility, however, that Mn minerals can be indicators of fracture-matrix interactions, colloid transport in fractures, and the role of aqueous emulsions on fracture surfaces in unsaturated-zone transport.

8. Work to be Done

Over the next few months, the data base of ^{36}Cl analyses of ESF rocks will continue to grow, primarily through analyses of samples from the South Ramp, from niches constructed in the Main Drift for percolation studies, and from the two alcoves penetrating the Ghost Dance Fault. A subset of samples will be analyzed for two other bomb-pulse nuclides – technetium-99 and iodine-129 – to provide independent evidence for the interpretation of the elevated ^{36}Cl signals as being of bomb-pulse origin. If successful, this approach may also be used to test for the presence of bomb-pulse at locations where the ^{36}Cl levels are ambiguous. Efforts are also underway to measure chloride concentrations in pore waters extracted from the TSw hydrologic unit in the ESF, as a surrogate measure of infiltration rates feeding the flux at those locations. Large chloride concentrations develop where infiltration rates are low due to high rates of evapotranspiration, whereas small concentrations reflect high infiltration rates.
The evaluation of the structural significance of sample locations in the ESF that show evidence of bomb pulse ^{36}Cl will continue. Ongoing interpretive efforts, discussed in detail below, will include the structural evaluation of several important known bomb-pulse localities, including two at the beginning of the intensely fractured zone and the development of an overall conceptual model of structural features that govern fast pathways. The ultimate goal is to recommend how the conceptual model developed by this activity can be incorporated into numerical flow and transport models of the Yucca Mountain site.

8.1. Evaluating the Structural Significance of Sample Localities along the South Ramp of the ESF

Several aspects of the geologic setting of the South Ramp of the ESF differ markedly from that in the Main Drift or the North Ramp, and will be considered as the ^{36}Cl results are evaluated. The PTn hydrogeologic unit is roughly half the thickness observed in the North Ramp. The interval consists primarily of pumiceous pyroclastic fall and reworked material; the Pah Canyon and Yucca Mountain Tuffs are absent. The South Ramp is the only location where the ESF crosses a block-bounding fault (the Dune Wash fault) at the level of the Topopah Spring Tuff (Fig. 1). The South Ramp also crosses several large, structurally complex, dilatent fault zones (below Boundary Ridge) that are potential fluid pathways.

8.2. Evaluating the Possible Influence of Fracture Orientation on Preferred Flow Paths

In the present-day stress field, northeast-striking fractures are more likely to be open than fractures of other orientations. An evaluation of possible relationships between flow paths and fracture orientation will be possible following a full tabulation of the orientation of fractures at each sample location, to be completed in the upcoming months.

Fracture studies at pavements and natural outcrops have documented that tectonic joints are shorter and have rougher surfaces and more irregular traces than cooling-related joints in the same unit. Differences in joint size, roughness, and planarity between different joint types may influence flow paths. A tabulation of the interpreted genesis of fractures at each sample site, to be completed in the upcoming months, will allow an evaluation of the importance of specific types of fractures on the flow path.

8.3. Further Evaluation of the Interplay between Structural Features and Spatially Distributed Infiltration

Limited data from the Main Drift of the ESF allow the suggestion that faults containing a component of bomb-pulse ^{36}Cl tend to coincide with infiltration highs. However, several zones of moisture (as yet of unknown age or affinity) were encountered along the South Ramp of the ESF underneath the Dune Wash area. It is possible that in certain cases alluvium-filled washes represent zones of relatively high infiltration. Further evaluation of the interplay between structural features and spatially distributed infiltration will be possible when ^{36}Cl/Cl data are available from additional samples from faults that are currently being processed, including: 1) faults intersected in the North Ramp of the ESF and exposed on the surface on Azreal Ridge, 2) the Dune Wash fault and other large faults intersected by the South Ramp of the ESF.

8.4. Mineralogic and Petrologic Settings of ESF Samples

Mineralogic characterization of the entire ^{36}Cl sample set will continue. A larger data set will enable us to further evaluate some of the preliminary interpretations offered in this report. The newest ^{36}Cl data document the existence of a long segment of the ESF without evidence of fast paths, and the secondary mineralogy of samples from this interval should provide data for an excellent comparison with the zones containing bomb-pulse ^{36}Cl. A complete mineralogic data set will also allow us to achieve the best possible integration of the isotopic and structural data with geochronology studies based on dating secondary minerals. Detailed mineralogic and textural characterization of the paired sets of size separates and of textural subsamples from breccia zones will allow us to further interpret the significance of ^{36}Cl/Cl ratios within each set.

9. Conclusions

As of March 1997, 189 isotopic analyses are available for 173 ESF sample locations between Sta. 2 and 68. Most of the samples have corrected ^{36}Cl/Cl ratios ranging from 450×10^{-15} to 1200×10^{-15}, which is the postulated range within which the meteoric background signal has varied during the past 50 ky or longer. Based on statistical analysis of the ESF data, a sample with a ^{36}Cl/Cl ratio higher than a cutoff of 1250×10^{-15} is interpreted as being clearly elevated above meteoric background and most likely contains a component of bomb-pulse ^{36}Cl. At a few locations, ratios extend well above this threshold, to a maximum of 4100×10^{-15}, and are interpreted as indicating the presence of a component of bomb-pulse ^{36}Cl, i.e., evidence of fast paths. Zones in which multiple samples show indications of bomb-pulse ^{36}Cl appear to be associated with major faults mapped at the surface. No samples containing unambiguous levels of bomb-pulse ^{36}Cl have yet been detected in any of the 53 samples analyzed beyond Sta. 45, including a sample from the Ghost Dance fault.

Based on work to-date, the existence of fast pathways at Yucca Mountain, conducting infiltration to depths as great as 300 m in 40 years or less, is tied to several criteria. The fast pathways are distinctive in terms of their structural settings and the associated hydrologic properties of those structures. The primary controls on the distribution of bomb-pulse ^{36}Cl in the ESF, ranked by importance, are: 1) the presence of faults that cut the PTn hydrogeologic unit; 2) the magnitude of surface infiltration; and 3) structural features that result in lateral diversion of flow away from fault zones. Bomb-pulse values are associated with a variety of fault types, including: 1) a block-bounding fault (Bow Ridge fault); a probable strike-slip fault (Drill Hole Wash fault); and smaller, intrablock faults (Sundance fault). In some instances, the projected locations of bomb-pulse samples in the ESF do not appear to correspond to a fault mapped at the surface, yet the high ^{36}Cl/Cl values may nonetheless indicate the likely existence of a fault that cuts the PTn hydrogeologic unit.

There does not appear to be any association between the presence or absence of bomb-pulse ^{36}Cl and the type of fault, orientation of fault, or amount of offset. The Sundance fault exemplifies a transmissive structural feature with lateral diversion of flow. Lateral diversion of flow below the level of the PTn hydrogeologic unit is most likely within the middle nonlithophysal zone of the Topopah Spring Tuff where large, relatively closely spaced cooling joints and the common presence of gently dipping cooling joints promote fracture network connectivity and the chances of a connected pathway in the rock mass surrounding the fault.

Preliminary mineralogic and petrologic analysis of 39 samples in the ^{36}Cl data base suggest that fast pathways may have some subtly distinctive mineralogic characteristics. Calcite, a common mineral in ESF fractures, is even more common in bomb-pulse samples, and is very common in samples from an interval with numerous bomb-pulse sites. However, this criterion alone is insufficient to predict the locations of fast paths. It has been qualitatively observed that the calcite deposits in fast-path transmissive features are much thinner than the cm-scale deposits utilized for ^{230}Th/U geochronologic studies of mineral deposition and inferred infiltration rates. It remains to be determined whether fast-path calcites record a different depositional history. Opal, unlike calcite, appears to be less common in fast pathways than its overall abundance in the ESF would suggest.

Clay deposits that coat fractures or breccia clasts are assumed to result from aqueous transport of fine clay particles within the fracture network and are unlikely to have been derived from the adjacent rock matrix. The mineralogic data set does not indicate a consistent connection between fast paths and the presence of clay/mordenite. However, fast-path sites associated with the Sundance fault are closely correlated with the presence of clay/mordenite deposits.

In addition to clay, there are deposits of coarser particulate materials as well. One prominent example in the Topopah Spring Tuff is a deposit clearly indicative of particle settling in a water-filled fracture. This sample has no bomb-pulse signature. The material in this deposit was probably transported before the PTn nonwelded tuffs were emplaced on top of the Topopah Spring Tuff. Particulate deposits such as this may relate more to ancient than to present fast pathways as far as the Topopah Spring Tuff is concerned. However, the presence of translocated particulates within a flow path attests to at least the local existence of connected pore spaces with apertures large enough to permit the passage of the particulates.